Nadir altimetry Vis-à-Vis swath altimetry: A study in the context of SWOT mission for the Bay of Bengal*

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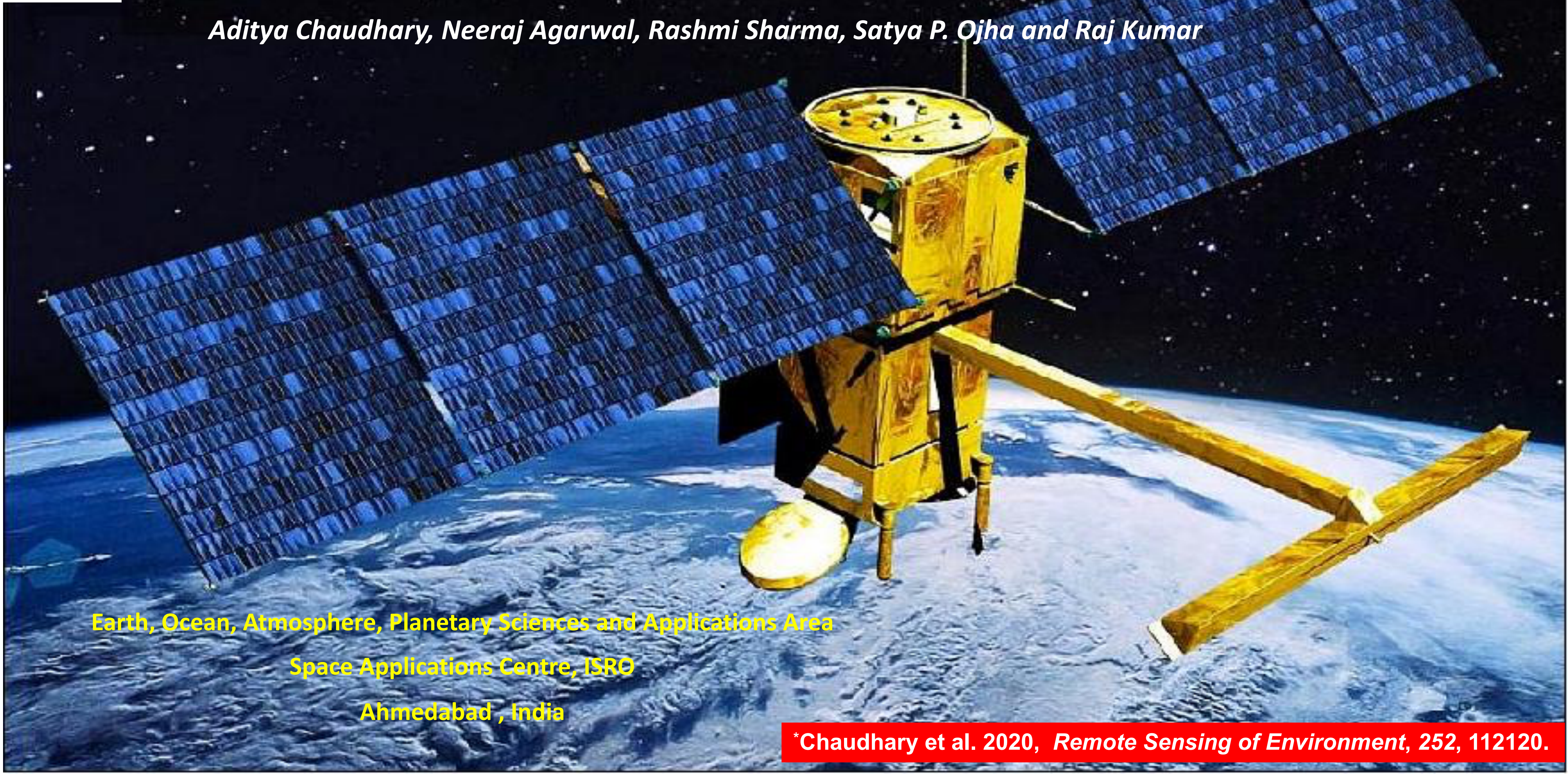

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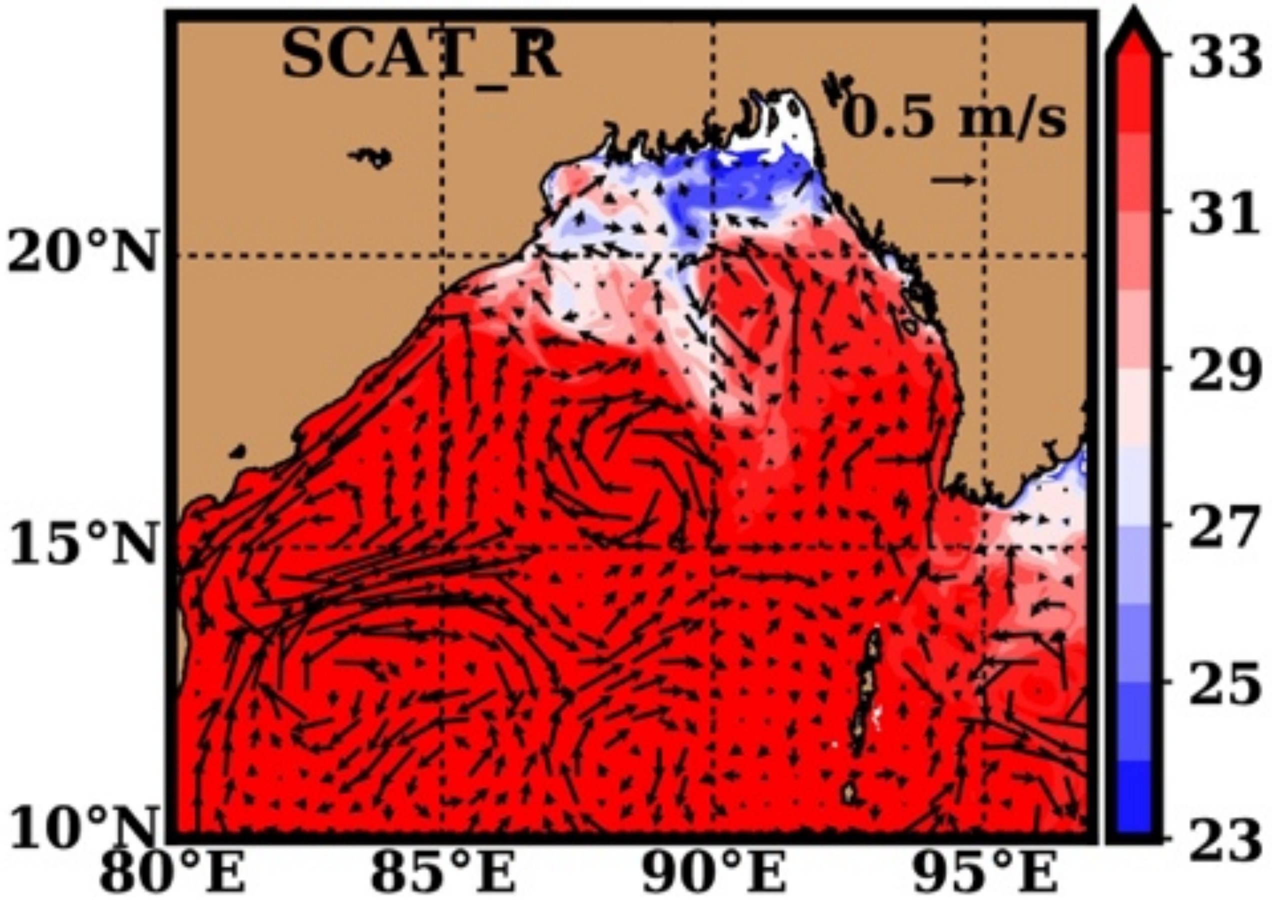
*Chaudhary et al. 2020, *Remote Sensing of Environment*, *252*, 112120.

Challenges in the Bay of Bengal

- Monitoring mesoscale/sub-mesoscale eddies that trap/transport fresh water
- The southward dispersal of fresh water is affected by sub-mesoscale to mesoscale eddies and filaments
- Nadir altimeters with 10 day repeativity miss many of the Bay of Bengal dynamics.
- Observing mesoscale and sub-mesoscale eddies in altimeter data even with a constellation of nadir altimeters is a much bigger challenge due to smoothening of features while gridding, for which SWOT definitely opens up an opportunity.



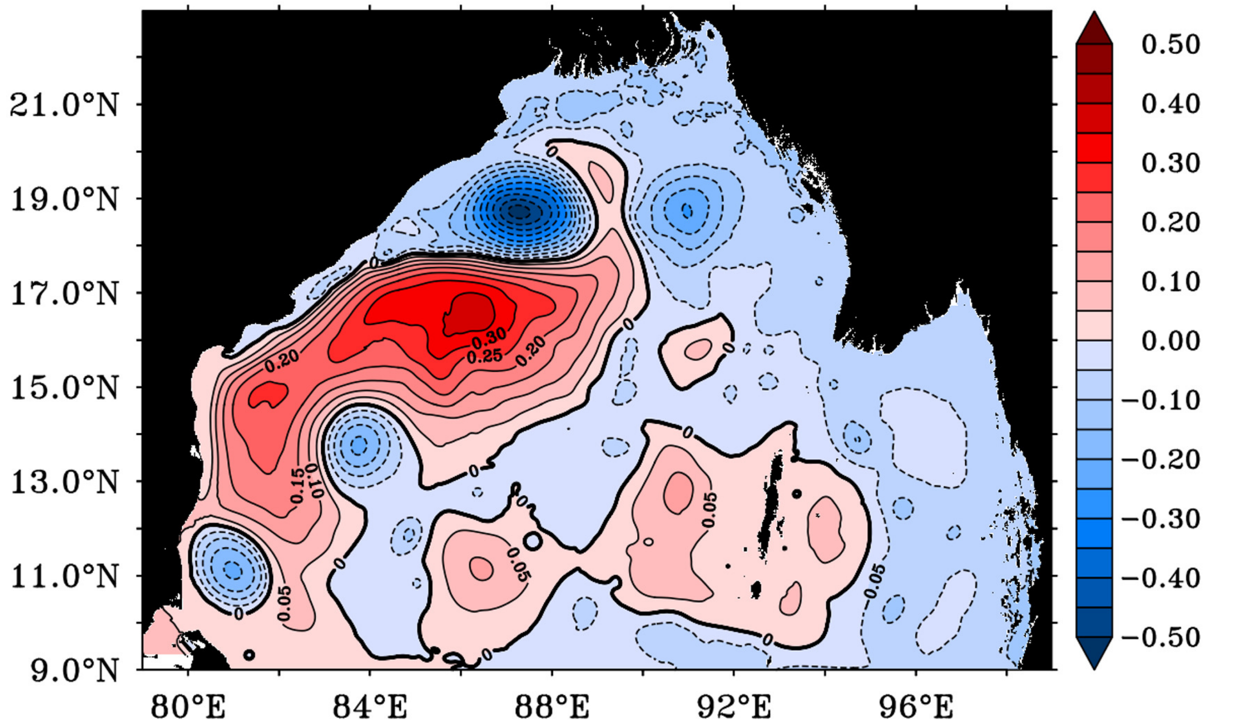
Sea Surface Salinity (psu) overlaid by vectors of sea surface currents (m/s) for 28th Sep 2017 from a high resolution model. Ratheesh et. al. 2020.

Questions to be addressed

- What is the optimum temporal resolution sampling required for SWOT required in the Bay of Bengal region ?
- What is the optimum gridding resolution for gridding the SWOT data for Bay of Bengal ?
- What is the scale of features that are resolved by the gridded SLA from SWOT as well as the SWOT-Like SLA. In Bay of Bengal in comparison to nadir altimeters ?
- What are the new challenges in computing the gridded SLA from SWOT data as well as the SWOT-Like SLA ?
- How to handle SWOT errors during mapping?

Tools and data used

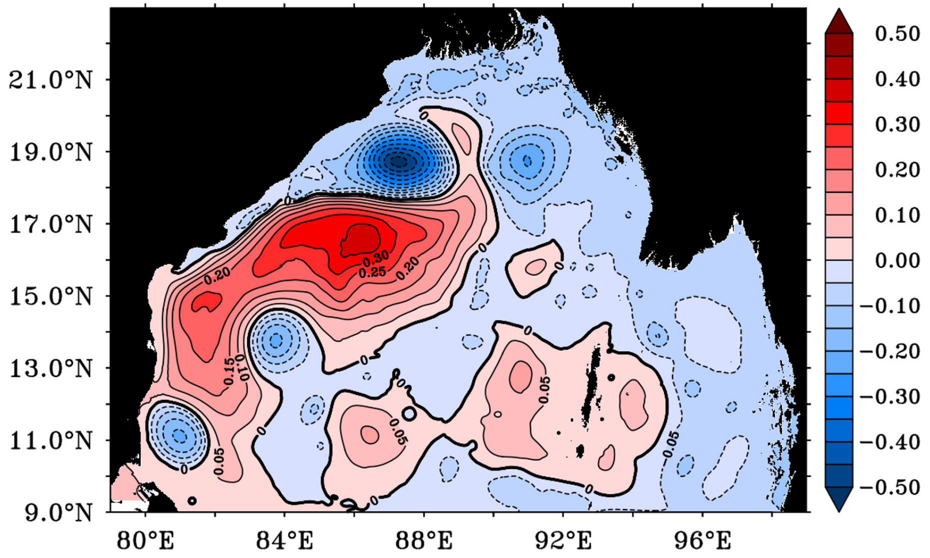
- **SWOT Simulator used to generate swath and nadir altimeter data over their tracks**
- **Numerical ocean model configured for the Bay of Bengal (0.02 °× $0.02° \; spatial \; resolution$) .**
- **SWOT simulator adds realistic noise to the model data.**
- **Period of simulations used: 2015**

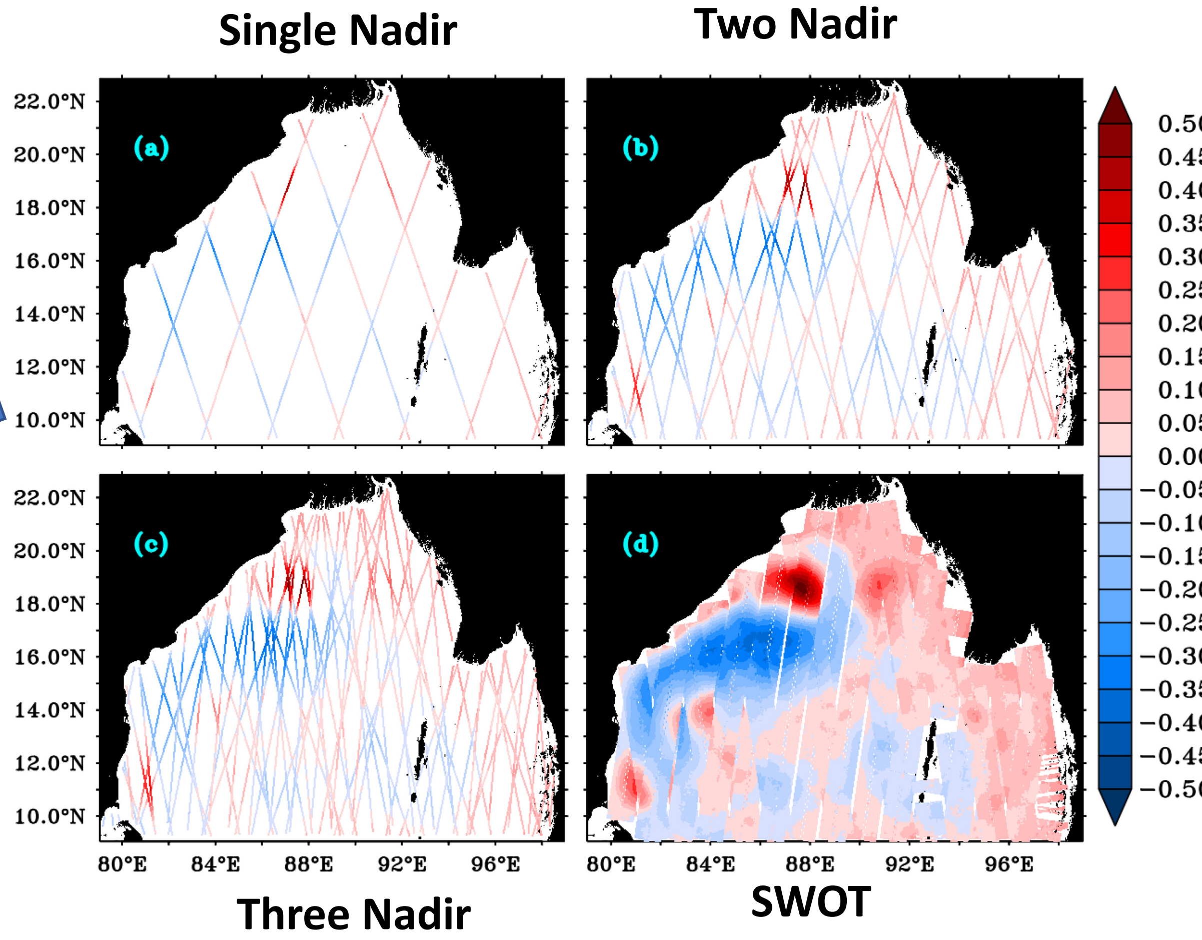


High resolution model simulated Sea Level Anomaly (m) for a particular day (11-Jan- 2015).

In the present study, we have used the SWOT simulator ([Gaultier et al., 2016]) available on [http://swot.jpl.nasa.gov/science/resources/]. This simulator uses SLA simulated from ocean model (as discussed above) and interpolates the field over SWOT like grid along the proposed science orbit of SWOT with a repeat orbit of 20.86 days. The simulator also generates random realizations of instrument errors and noise over the SLA, as well as simulated geophysical errors. The quantification of these errors is provided by the SWOT project team.

SWOT Simulator





(a) Jason-2 simulated SLA (m) for a particular day (11-Jan-2015) +/-10 days, similar simulations for (b) J2 + SRL (c) J2 + SRL+ C2 and (d) SWOT. Regions in which land was present in the swath is masked.

The instrument errors included in the simulator can be described as KaRIN instrument noise, the roll errors, phase errors, baseline dilation errors and the timing errors. The KaRIN noise is random Gaussian zero-centered type which varies with distance to the nadir and Significant wave height in the simulator. Roll errors comprise of gyro error and the roll control errors. The phase errors are the systematic errors introduced due to changes in relative phase between the two signal paths in the interferometric pair. Baseline dilation errors are the errors in change of baseline length of interferometer which creates a quadratic height error across the swath. Timing errors correspond to group timing delay errors which introduce errors in the height calculation. For simulating the geophysical errors only, the wet tropospheric error is simulated, this error has highest variability in space and time. For simulating nadir data from altimeters a user defined white noise is added to the along track data in the SWOT simulator.

Mapping Technique

The optimum field θ_{est} according to the **Le. Treon et al. 1998** is given by

$$\theta_{est}(x) = \sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij}^{-1} C_{xj}\, \Phi_{obs^i}$$

where $\Phi_{obs^i} = \Phi_i + \varepsilon_i$, Φ_i is the true value

and ε_i is the measurement error

A is the covariance matrix for the observations and
C is the covariance vector for the observations and field to be estimated.

$$A_{ij} = \langle \mathbf{\Phi}_{obs^i} | \mathbf{\Phi}_{obs^i} \rangle = \langle \mathbf{\Phi}_{obs^i} | \mathbf{\Phi}_{obs^i} \rangle + \langle \varepsilon_i | \varepsilon_j \rangle \quad \text{and}$$

$$C_{xi} = \langle \theta(x)\Phi_{obs^i} \rangle = \langle \theta(x)\Phi_i \rangle$$

Same technique as suggested by Le Traon et al. (1998).

Long wavelength components of the instrument errors are not considered while mapping SLA.

The interpolation method is "sub-optimal" i.e. the data is selected in a specific space-time subdomain such that only the observations nearest to the grid point are considered (Le Traon et al., 1998).

The interpolation technique uses a priori statistical knowledge of both the covariance functions of the signal to be mapped and the noise present in the signal.

Observation errors in SLA were taken to be similar (~100 cm2/cpkm) for all the nadir altimeters (Jason-2, SARAL/AltiKa, Cryostat-2, and on altimeter in SWOT).

Modelling of Errors for SWOT

There are six types of errors which are modelled in SWOT Simulator.

For calculating the gridded field from the individual observations, the optimal interpolation method requires covariance matrix Aij for the SLA observations. Following Le Traon et al. (1998), covariance matrix is formulated as:

Covariance matrix for the observations term

$$A_{ij} = \langle \boldsymbol{\Phi}_{obs^i} | \boldsymbol{\Phi}_{obs^i} \rangle = \langle \boldsymbol{\Phi}_{obs^i} | \boldsymbol{\Phi}_{obs^i} \rangle + \langle \varepsilon_i | \varepsilon_j \rangle$$

The $\langle \varepsilon_i \varepsilon_j \rangle$ term can be decomposed as

$$\langle \varepsilon_i \varepsilon_j \rangle = \langle \varepsilon_i \varepsilon_j \rangle_{corr} + \langle \varepsilon_i \varepsilon_j \rangle_{uncorr}$$

$\varepsilon_i\ \varepsilon_j = 0\ , i \neq j$ ➔ Errors are treated as uncorrelated

$\varepsilon_i\ \varepsilon_j = \delta_{ij}\ , i \neq j$ ➔ Errors are treated as correlated

We have performed 5000 simulations along an arbitrary SWOT pass in the Bay of Bengal to model the noise in SWOT. Details given in Appendix of Chaudhary et. al. 2020

2-D Guassian function has been used

$$\text{Gausssian function G} = A * exp(-\alpha * (x - x_0)^2 - \beta * (y - y_0)^2) + c$$

where $x_0, y_0, A, \alpha, \beta$ and c are various parameters determined by fitting. In order to use two independent 2-D Gaussian following formulation can be used

$$\text{Correlation function} = G_1 * sigmum(x) + G_2 * signum(-x)$$

$$\text{where } sigmum(x) = \begin{cases} 1 & when\ x > 0 \\ 0 & otherwise \end{cases}$$

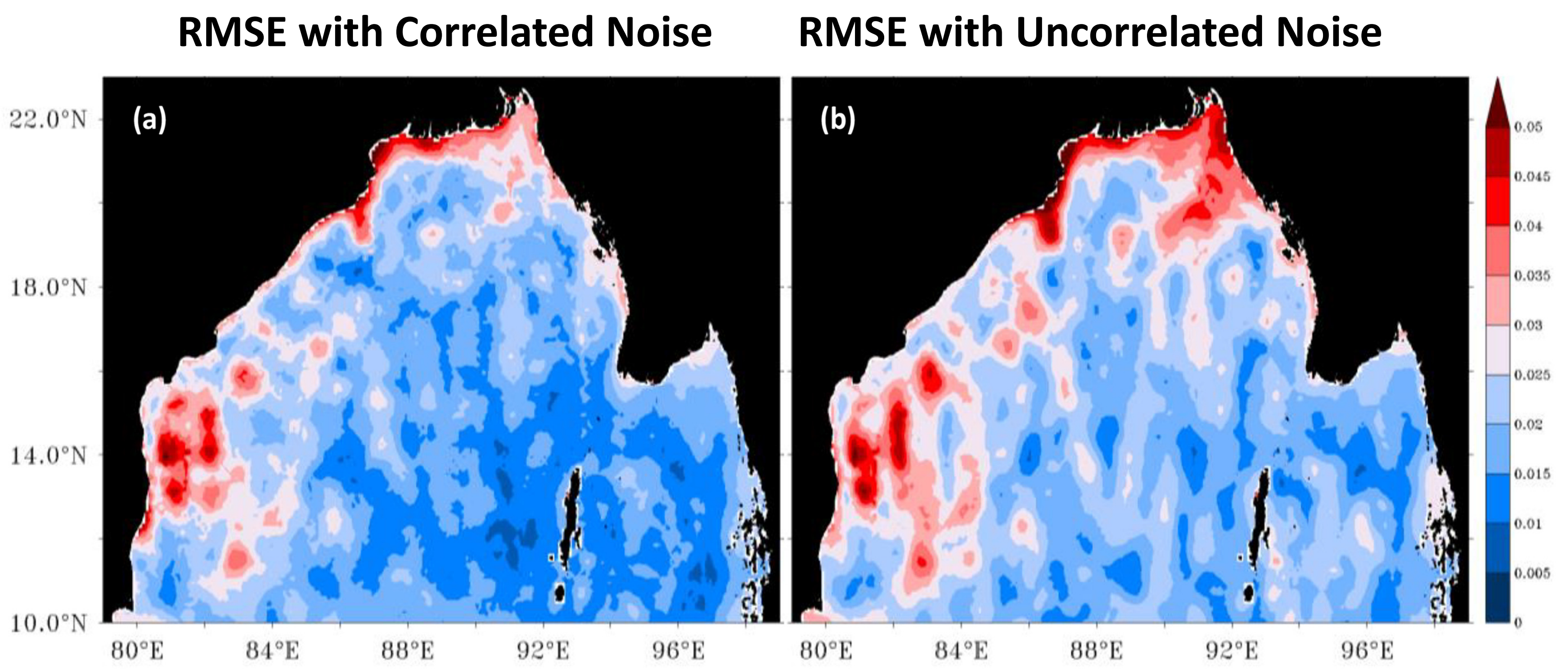
and G_1 and G_2 are the two 2-D Gaussian functions.

Mapping procedure

- Temporal and spatial sampling scale for gridding nadir SLA fields, decorrelation scale analysis was performed on model-simulated SLA for the Bay of Bengal region, similar approach to Kuragano and Kamachi (2000)
- Temporal and spatial scales of SLA decorrelation spatial and temporal scales in the BoB region were found to be 120 km and 10 days respectively.
- Simulated SLA field from SWOT simulator were smoothed by using a 1-D Lanczos filter (cutoff 50 km) for nadir altimeters and 2-D Lanczos (cutoff 15 km) filter for SWOT.
- Sensitivity of mapping to type of noise, spatial and temporal sampling was studied by several experiments
- 120 days of simulated data was used for generating maps.

Sensitivity of mapping to correlated and uncorrelated noise

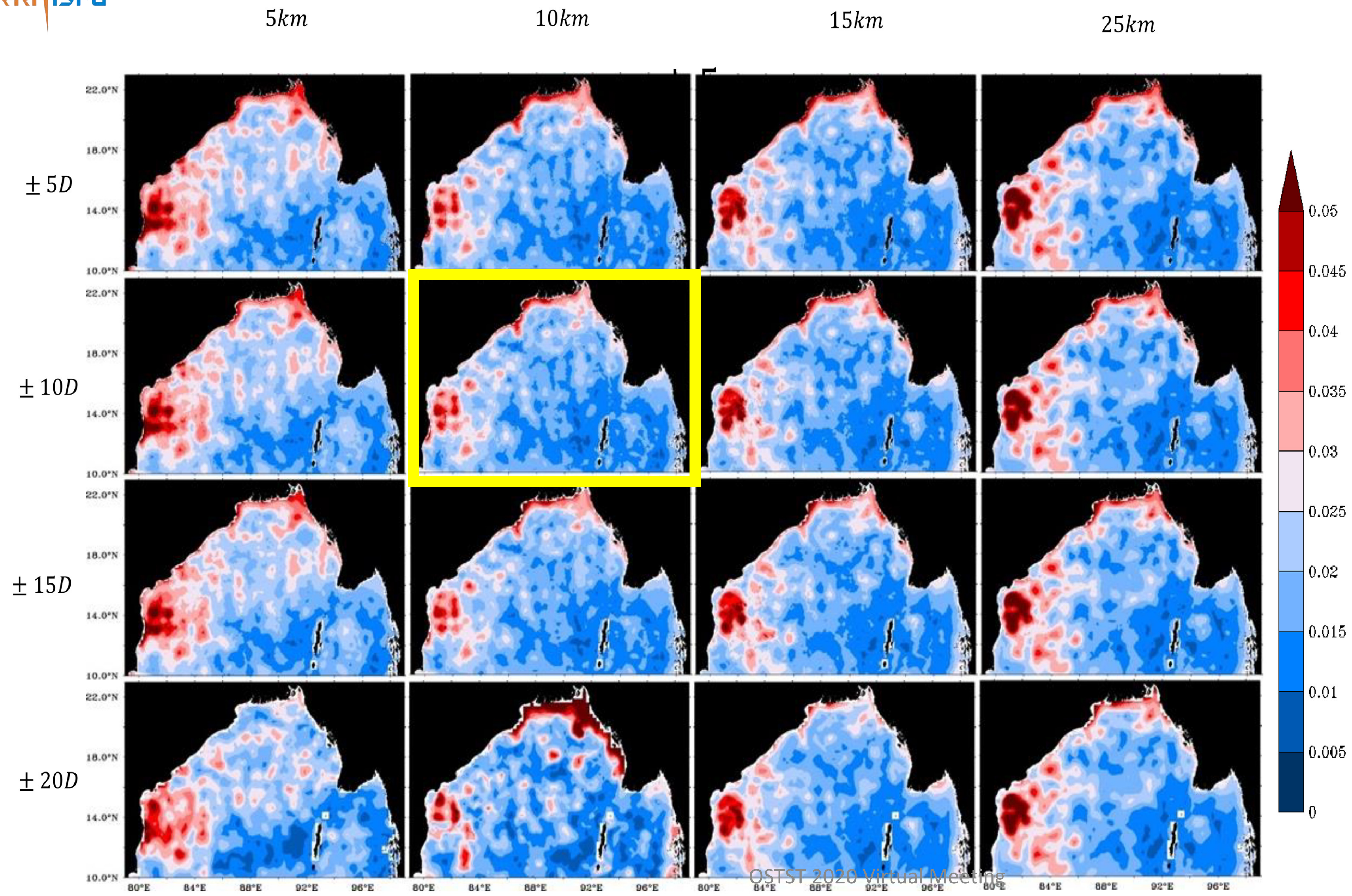
- Correlation functions have been modeled using two independent 2-D Gaussian functions to the observed error based on 5000 simulations .
- Another case, in which the noise is considered as uncorrelated, the off diagonal terms in the error covariance function ⟨εiεj⟩ are set to zero.
- Hence, two gridded fields of SLA were prepared using SWOT data, one including correlated noise and the other one assuming that the noise is uncorrelated.
- RMSE maps of both the SLA fields computed with respect to the model simulations.



Maps of RMSE (m) for gridded SLA fields generated using (a) Correlated and (b) Uncorrelated noise. The description of these noise is provided in Chaudhary et. al. 2020

It is observed that by modelling the correlated noise there is a significant reduction in RMSE as compared to the case when correlated noise is not considered. SLA mapped fields for the rest of this study have been generated using the modelled correlated noise.

Sensitivity of mapping to spatial resolution and temporal sampling



RMSE (m) of Gridded SLA from SWOT w.r.t. model simulations for different combinations of spatial resolution and temporal sampling of satellite swaths.

The error patterns for all the combinations are grossly similar indicating that the spatial resolution and temporal sampling of SWOT observations do not result in significant loss in the observed signal. Quantitatively however, it can be clearly seen that the RMSE is least when spatial resolution of 10 km is considered (highlighted by yellow box)

Sensitivity of mapping to spatial resolution and temporal sampling

Spatial Resolution/ Temporal scale	5 km	10 km	15 km	20 km
5 days	0.0242	0.02107	0.0218	0.02305
10 days	0.0242	$\boxed{0.02087}$	0.02178	0.02301
15 days	0.02424	0.02107	0.02187	0.023
25 days	0.02279	0.02467	0.02147	0.0231

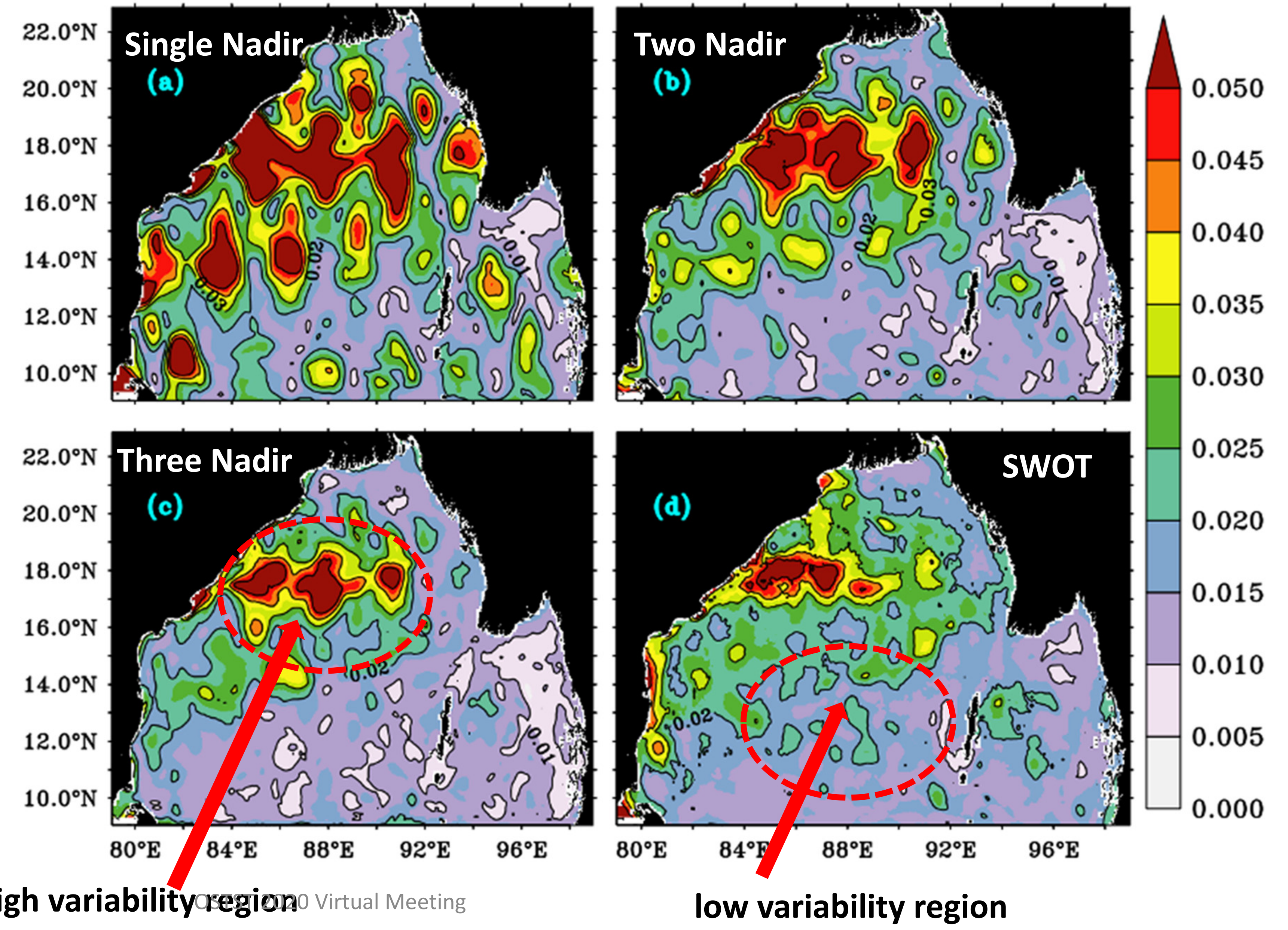
SLA mapping root Mean square errors (m) for the entire Bay of Bengal domain for different spatial resolution and temporal sampling considered for SWOT data. The errors are least for 10km x 10km spatial and $\pm$10 days temporal sampling in the Bay of Bengal

Assessment of Mapped fields for the Bay of Bengal

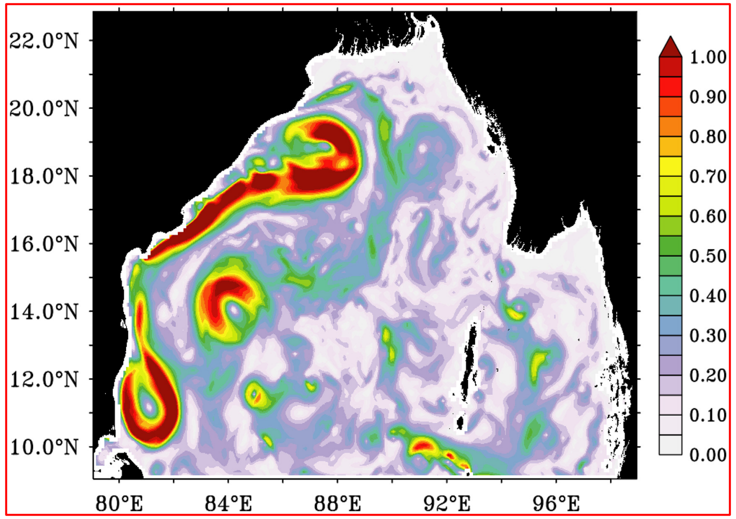
RMSE (m) of SLA for 120 days for (a) single altimeter (b) two altimeters (c) three altimeters and (d) SWOT.

Large Errors in single altimeter and least in SWOT

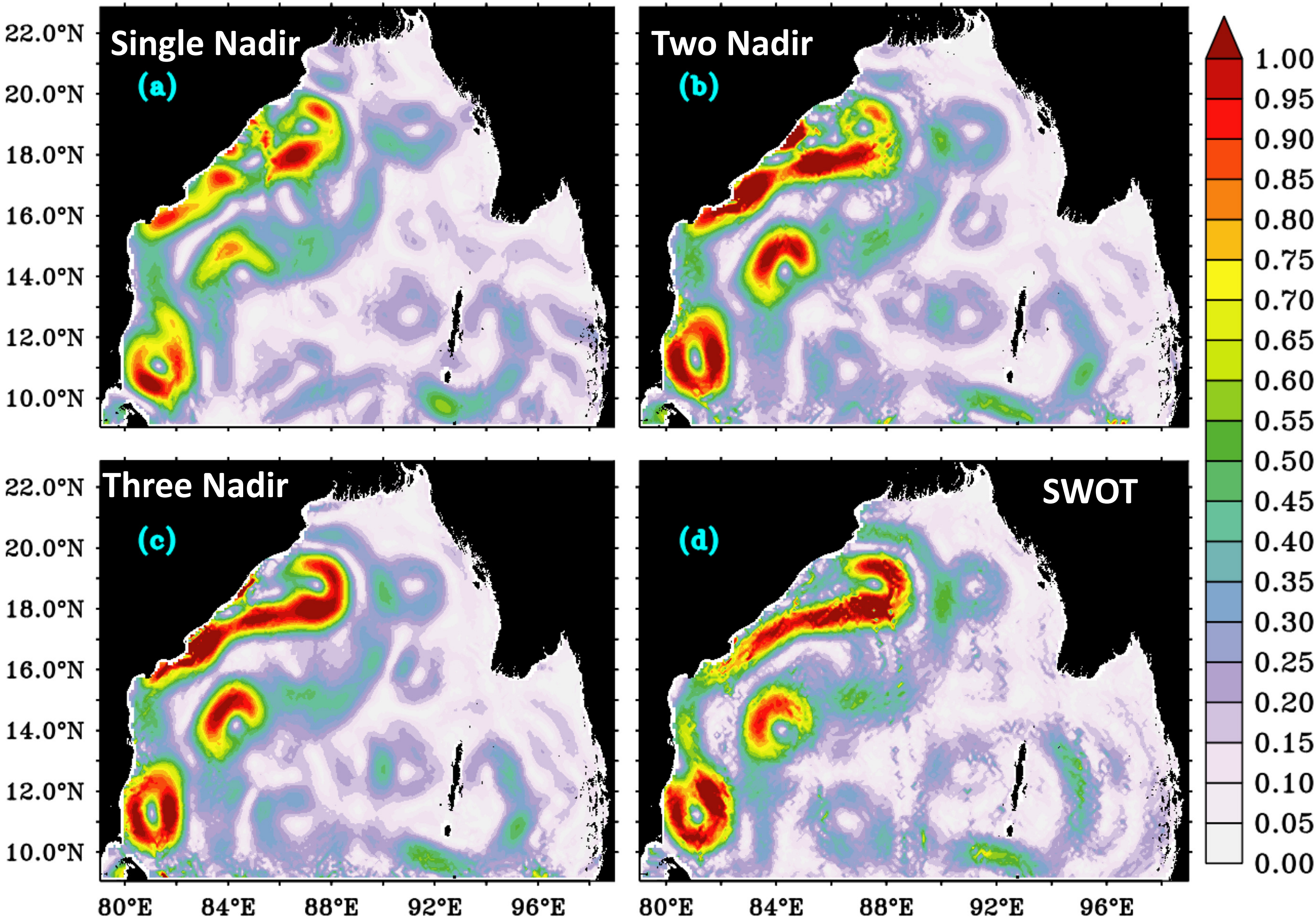
SWOT errors are less in high variability regions as compared to 3-Nadir altimeter combinations, while in low variability regions, the mapped product from 3-nadir altimeter is better.



Mapped Geostrophic currents



Model simulated SLA derived geostrophic current magnitude (m/s) for a particular day (11 Jan-2015).



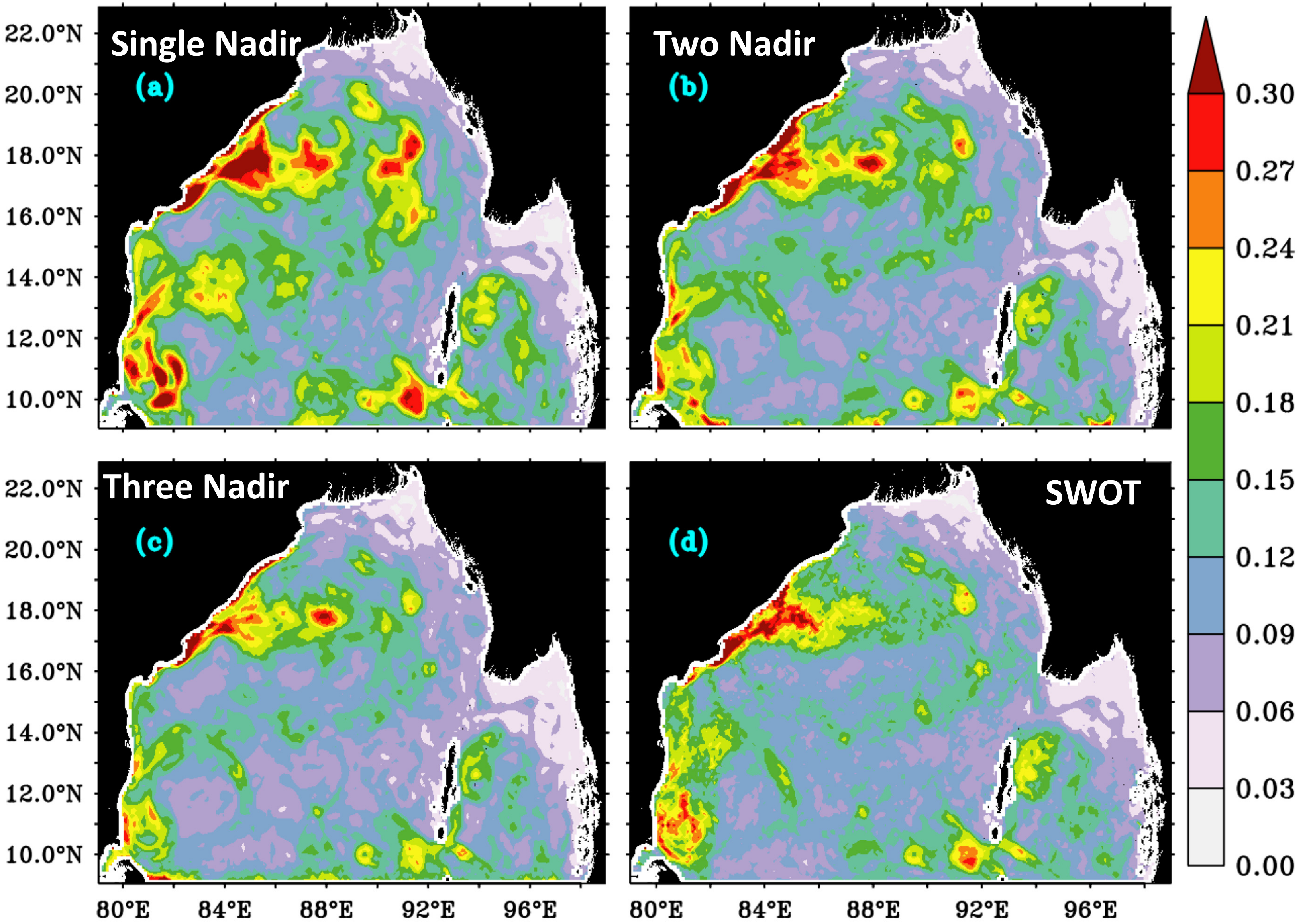
Geostrophic current magnitude (m/s) for a particular day from (a) single (b) two (c) three nadir altimeters and (d) SWOT.

Errors in mapped Geostrophic Currents

Regions of high variability in currents encounter maximum errors

Errors reduce with more number of altimeters

SWOT have similar errors as 3 nadir altimters.

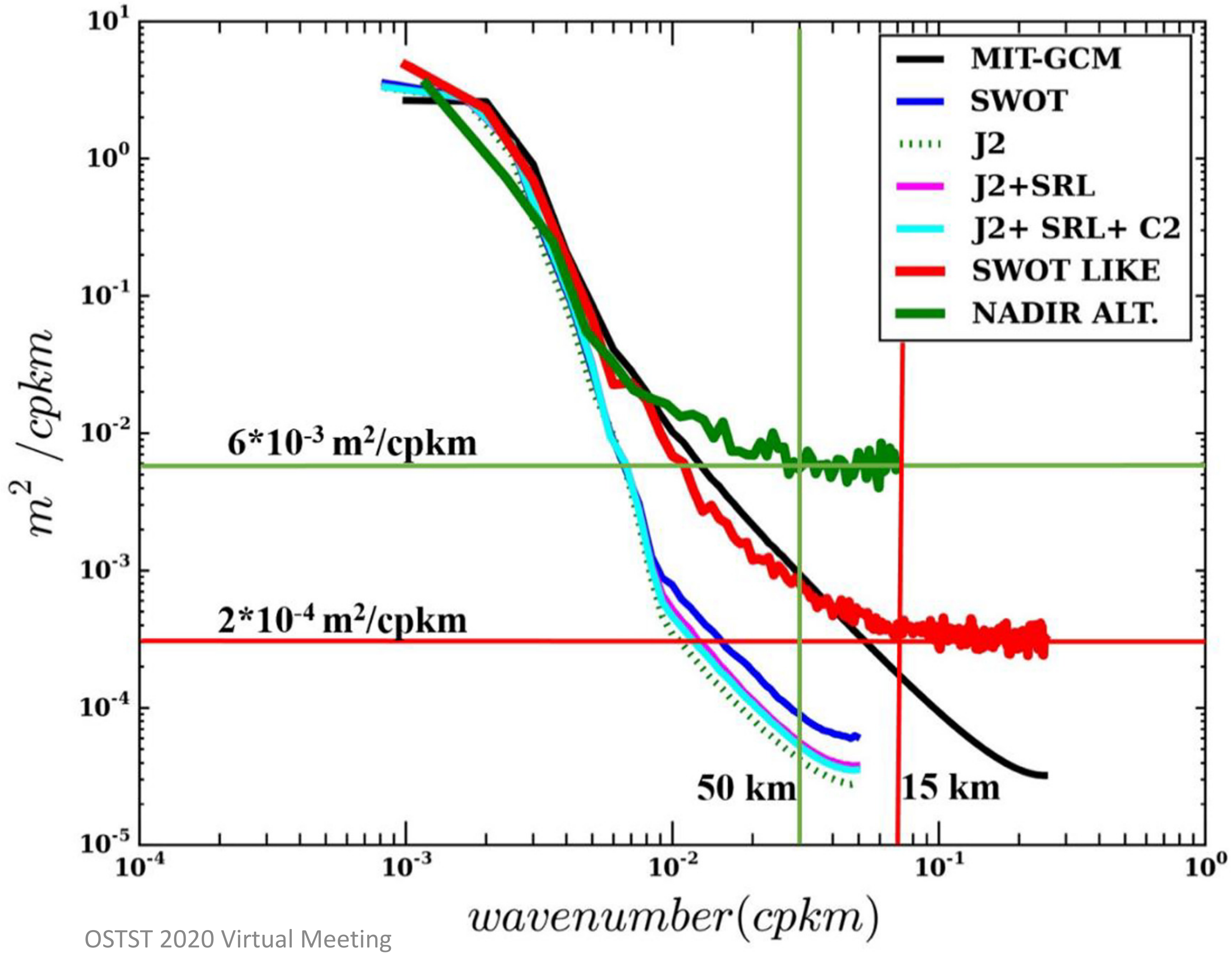


RMSE (m/s) of mapped geostrophic velocity for different combinations of altimeter

Power Spectrum Analysis

The power spectrum of the mapped fields from nadir and SWOT altimeters is almost similar. It can be seen from the figure that PSDs of mapped fields (J2, J2+ SRL, J2 + SRL+ C2 and SWOT) diverges from PSD of model SLA beyond wavenumber 0.005 cpkm. This essentially means that mapped SLAs are not able to resolve the features with wavelength lower than 200 km.

SWOT-like observations accurately represent scales up to 50 km



Summary

- Correlated errors have been modelled to use in the mapping of SWOT.
- Mapped SLA with correlated errors are better than SLA maps in which errors are uncorrelated.
- Sensitivity of mapping of SWOT SLA to various spatial resolutions and temporal sampling studied.
- Mapped SWOT SLA is better than map of 3 nadir altimeters in the region of high sea level variability.
- Spectral analysis show that SWOT captures sub-mesoscale variability realistically.
- Need for an alternate approach for mapping SWOT observations (dynamical interpolation)

THANKS